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ORIGINAL

Multi Responses Optimization of Wire Electrical Discharge Machining (WEDM) Parameters of Tool Steel Using Grey Relation Analysis

Optimización multirrespuesta de los parámetros de mecanizado por descarga eléctrica de alambre (WEDM) de acero para herramientas mediante análisis de relación de grises

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ABSTRACT

The aim of this work is to study the effects of several wire electrical discharge machining (WEDM) process parameters, such as the servo voltage (SV), the pulse on time (T_{ON}), and the pulse off time (T_{OFF}) on the surface finish (SR) and the kerf width (KW) of stainless steel 304 as a workpiece material. A multi-responses optimization approach based on Grey relational analysis has been designed, and it was discovered that the main affecting factor is the pulse on time followed by the servo voltage. According to the data, the grey relation analysis (GRA) grade for the second trial, including (a servo voltage of 14V, a pulse on time of 100µs, and a pulse off time of 45µs), was the optimum combination of settings that may concurrently optimize all of the specified response qualities. By utilizing the regression analysis, the mathematical equations illustrating the link between the input parameters and the responses have been established. In particular, the findings of this article will assist manufacturing engineers in selecting an optimal set of process parameters for machining stainless steel (SS304) grade.

Keywords: WEDM; SS304; Grey Relation Analysis; Kerf Width; Surface Integrity; Regression Equation.

RESUMEN

El objetivo de este trabajo es estudiar los efectos de varios parámetros del proceso de mecanizado por descarga eléctrica de hilo (WEDM), tales como el servo voltaje (SV), el tiempo de encendido del pulso (TON), y el tiempo de apagado del pulso (TOFF) sobre el acabado superficial (SR) y la anchura de la sangría (KW) del acero inoxidable 304 como material de la pieza. Se ha diseñado un enfoque de optimización multirrespuesta basado en el análisis relacional de grises, y se ha descubierto que el principal factor que afecta es el tiempo de encendido del pulso seguido del servo voltaje. De acuerdo con los datos, el grado de análisis de relación gris (GRA) para el segundo ensayo, incluyendo (un servo voltaje de 14V, un tiempo de pulso de 100µs, y un tiempo de pulso de 45µs), fue la combinación óptima de ajustes que pueden optimizar concurrentemente todas las cualidades de respuesta especificadas. Utilizando el análisis de regresión, se han establecido las ecuaciones matemáticas que ilustran el vínculo entre los parámetros de entrada y las respuestas. En particular, los resultados de este artículo ayudarán a los ingenieros de fabricación a seleccionar un conjunto óptimo de parámetros de proceso para el mecanizado de acero inoxidable (SS304).

Palabras clave: WEDM; SS304; Análisis de la Relación de Grises; Anchura de la Sangría; Integridad Superficial; Ecuación de Regresión.

INTRODUCTION

The electrical discharge machining (EDM) technique is one of the practical solutions for machining an expanding variety of tough, wear-resistant, and non-corrosion materials using sparks. On the other hand, wire electrical discharge machining (WEDM) is a process where the material is removed via a sequence of sparks from the workpiece. Particularly, a moving wire electrode that goes through the workpiece is utilized in the wire EDM. A Computer-Numerically Controlled (CNC) machine is carefully monitored. WEDM, like any other machining tool, removes the material. However, WEDM eliminates the material electrically by spark erosion. As a result, EDMed materials must be electrically conductive. As a Direct Current (DC) between the wire electrode and the workpiece, electrical pulses are created(1,2,3) as illustrated in figure 1 Khan et al.(4) examined the impact of WEDM parameters on the SR and the KW of the stainless steel, and they found that the surface roughness was effectively influenced by the pulse on time T_{ON}. In addition, the analysis of variance (ANOVA) results revealed that the T_{ON} was the most impacting factor on SR. Bobbili et al.(5) examined three performance factors, including SR, MRR, and gap current (GC). In particular, four different machining factors were tested, namely the T_{ON}, the spark voltage, the peak current (I), and the T_{OFF}. From the results, it was revealed that the T_{ON}, the peak current, and the spark voltage were significantly effective on SR. In another study, Boujelbene et al.(6) examined different WEDM process parameters, including the T_{ON}, the SV, and the peak current (I) on the SR, and it was found that the SR increases as the SV increases. The T_{ON} was found to be a critical parameter for the WEDM, where increasing it generates a significant variance in the SR parameters, resulting in rough surfaces. Furthermore, Hong et al.(7) examined the effects of WEDM process parameters on the SR, and the impact of these parameters on SR was examined using the variance analysis. Specifically, the study results showed that the cutting voltage, the T_{ON}, the T_{OFF}, and the SV are all important impacting parameters on the SR. Additionally, Rao et al.(8) determined the ideal combinations from the results of calculating the multi-performance, which revealed that the T_{OFF} and the SV have the greatest effect on the multi-response. Hema et al.(9) investigated the optimum set of input parameters, including the T_{ON}, the wire tension (WT), and the T_{OFF} in WEDM. In particular, their experiment described the variation in the SR and the kerf width when three process parameters were changed. The Taguchi approach based on the grey relation was employed in the analysis, and the findings showed that the pulse on time has a substantial influence on three output parameters. The ninth experiment revealed that a pulse on time of 150µs, a pulse off time of 40µs, and a wire tension of 14 kg-f are ideal process parameters. Moreover, Azwan et al.(10) found that, according to the statistical analysis (ANOVA), the intensity of the process dielectric fluid pressure with nano powder has a significant effect on the enhanced surface roughness. The best result of (2,87 µm) was obtained in the surface roughness, and this is considered an improvement rate of 95%. The influence of the process parameters of the applied voltage, the traverse feed, the T_{ON}, the T_{OFF}, and the current intensity on the surface roughness of stainless steel 304 was investigated by Noha Naeim et al.(11). Among the effect of the five process parameters, a current tension of (p-value 1,89 × 10−7), a T_{ON} of (1,602 × 10−5), and a T_{OFF} of (0,0204) were the most significant parameters influencing the surface roughness. Rawat et al.(12) investigated WEDM for AA6061. Particularly, the Taguchi's L18 OA matrix, the S/N ratio, the ANOVA, and the Grey relational analysis were used. According to ANOVA, the most important elements of SR are the T_{ON} and the peak current I, with contributions of 13,33 % and 16,25 %, respectively. Furthermore, the best feasible consideration parameters' setting for SR was achieved using GRA: where T_{ON} was 50µs, T_{OFF} was 13µs, and I was 4A. Das et al.(13) attempted to improve SR and KW using WEDM, where an experiment was carried out to investigate the influence of the machining factors, including the WT, the T_{ON}, and the T_{OFF}. It was found that T_{ON} is 130µs, T_{OFF} is 60µs, and WT is 11 kg-f for a smoother SR. While the optimal KW was achieved when T_{ON} is 130µs and T_{OFF} is 50µs. The main focus of this work was the optimization and experimental research of wire EDM machining on stainless steel (SS304) grade tool steel. The grey relation was completed, and the optimal setting was created.

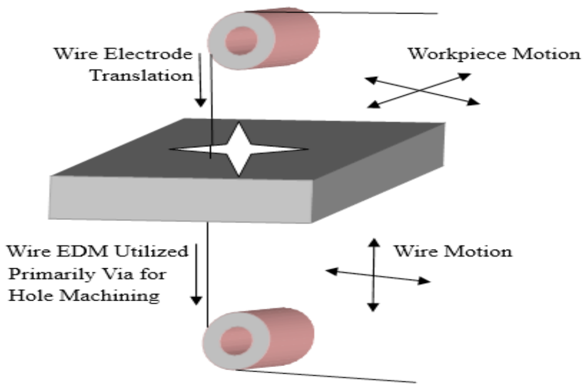

Figure 1. Schematic of the wire EDM Process

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Figure 2. The wire EDM Machine

Experimental Work

A machining operation was carried out for the experimental part using twenty-seven samples. Each sample was machined according to the specific cutting conditions, as shown in figure 2.

Selection of the workpiece material

The present work uses stainless steel (SS304) grade as a workpiece with 25×25×4 mm dimensions, as shown in figure 3. More specifically, stainless steel (SS304) grade specimens were tested using a WEDM machine (see figure 4 a and b). Table 1 illustrates the analysis of the chemical composition of the workpiece material of Stainless Steel 304.

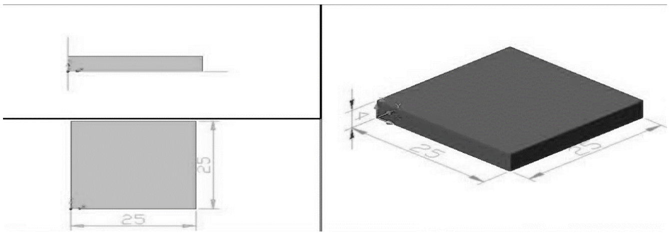

Figure 3. The Workpiece

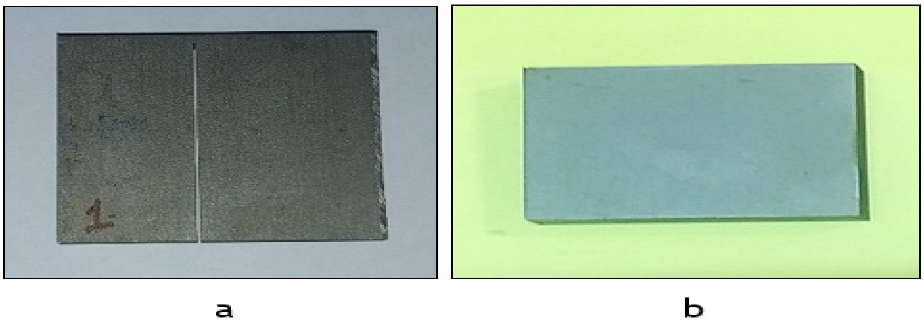

Figure 4. a) The Workpiece before Machining b) The Workpiece after Machining

Table 1. Chemical Composition of the SS304

Element	Concentration	Element	Concentration
C	0,0194	Nb	0,0451
Si	0,477	V	0,104
Mn	0,164	W	0,0297
P	0,0258	As	0,0017
S	0,0005	Ca	0,00053
Cr	18,71	Fe	Bal.
Mo	0,0899		
Ni	8,7		
Al	0,001		
Co	0,189		
C			
u	0,065		

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The instrument for measurement

The surface roughness tester was used to measure the surface roughness values, and the kerf width was measured by the metallurgical incident light microscope, as illustrated in figure 4 and 5.

Figure 4. The Surface Roughness Tester

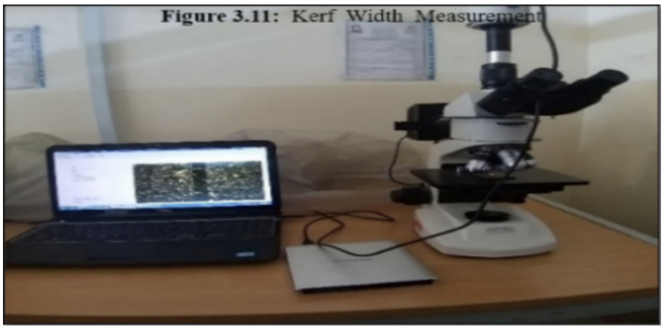

Figure 5. The Incident Light Microscope

Selection of Process Parameters and Experiments of Design

The number of trials required is heavily influenced by the design of experiments. As a result, the cutting experiments must be well-planned. The total number of cutting trials was 27, with three levels to obtain minimum surface roughness values, where a full factorial design was used. T_{ON}, T_{OFF}, and SV were the parameters under consideration. Table 2 shows the levels of the cutting parameters.

Table 2. Experimental Parameters and their Levels

Parameter	Unit	Level-1	Level-2	Level-3
Pulse on time	[µs]	100	110	120
Pulse off time	[µs]	45	50	55
Servo Voltage	[V]	10	14	18

The Grey relational analysis is a method for determining the degree of approximation between sequences by employing a Grey relational grade. The sections that follow describe the Grey relational analysis approach that was employed in this work to determine the best WEDM settings as well as the significant influential parameters that impact the kerf width and the surface roughness. Data preprocessing is used to convert a given data sequence into a dimensionless data sequence by transferring the original sequence to a related sequence. Let's represent the original reference sequence and the comparability sequence as x0(0)(k) and xi (0) (k), i = 1, 2, …, m; k = 1,2, ..., n, respectively, where m is the total number of experiments to be considered, and n is the total amount of observation data. The original sequence is converted into a similar sequence during data preparation. Depending on the parameters of the original sequence, several data preparation approaches can be utilized in the Grey relation analysis. The original sequence is normalized as follows for the "the-smaller the-better" feature.[14]

$$x_i^*(k) = \frac{\max(x_i^{(o)}(k)) - x_i^{(o)}(k)}{\max(x_i^{(o)}(k)) - \min(x_i^{(o)}(k))} \qquad (1)$$

The second step was to calculate the grey relation coefficient (GC), which was utilized to find the link between the optimum and the actual normalized output results. In particular, equation (2) was used for this calculation. The Grey relational coefficient is computed as:[6] Where Δ0i (k) is the deviation sequence of the reference sequence x0* (k) and the comparability sequence xi* (k).

$$\gamma(x_0^*(k), x_i^*(k)) = \frac{\Delta_{min}+\zeta\Delta_{max}}{\Delta_{oi}(k)+\zeta\Delta_{max}} \qquad 0 < \gamma(x_0^*(k), x_i^*(k)) \le 1 \qquad (2)$$

$$\Delta_{oi}(k) = |x_0^*(k) - x_i^*(k)|, \qquad (3)$$

$$\Delta_{max} = max_{\forall j \in i} max_{\forall k} |x_0^*(k) - x_j^*(k)|$$

$$\Delta_{min} = min_{\forall j \in i} min_{\forall k} |x_0^*(k) - x_i^*(k)|$$

Where ζ is the distinguishing coefficient, $\zeta \epsilon$ [0,1]. The Grey relational grade is produced using the following connection once the grey relational coefficients have been calculated.(14)

$$\gamma(x_0^*, x_i^*) = \sum_{k=1}^{n} \beta_k \gamma(x_0^*(k), x_i^*(k)), \text{ where } \sum_{k=1}^{n} \beta_k = 1$$

The degree of connection between the reference and the comparability sequences is represented by the Grey relational grade ɣ (x0*, xi*). When two sequences are similar, the Grey relational grade is equal to 1. Moreover, the Grey relational grade also reflects how much effect the comparison sequence has on the reference sequence. As a result, if one comparability sequence is more essential to the reference sequence than others, the Grey relational grade for that comparability sequence and the reference sequence will be higher than other Grey relational grades. Particularly, the Grey relational analysis is a measurement of the absolute value of data difference between the sequences that may be used to approximate correlation.(14)

RESULTS AND DISCUSSION

The variable experimental matrix was used to create twenty-seven trials (see table 3). For each and every experiment, the L27 orthogonal array was utilized.

Table 3. The design of experiments (DOE) and the measured surface roughness and the kerf width levels

Run no.	Std Order	Pt Type	Blocks	Servo Voltage [V]	Pulse - on [µs]	Pulse-off [µs]	Surface Roughness [µm]	Kerf Width [µm]
1	14	1	1	14	110	50	1,806	305,583
2	10	1	1	14	100	45	1,222	246,404
3	3	1	1	10	100	55	1,101	330,375
4	22	1	1	18	110	45	1,567	301,584
5	13	1	1	14	110	45	1,490	308,783
6	27	1	1	18	120	55	2,494	315,182
7	5	1	1	10	110	50	1,871	298,389
8	9	1	1	10	120	55	2,471	322,381
9	17	1	1	14	120	50	1,484	309,583
10	4	1	1	10	110	45	1,695	299,989
11	20	1	1	18	100	50	1,384	263,985
12	12	1	1	14	100	55	1,201	294,379
13	6	1	1	10	110	55	1,787	286,381
14	18	1	1	14	120	55	2,409	323,981
15	23	1	1	18	110	50	2,729	301,589
16	15	1	1	14	110	55	1,632	305,578
17	26	1	1	18	120	50	2,579	303,184
18	16	1	1	14	120	45	2,748	290,385
19	21	1	1	18	100	55	1,379	319,176
20	11	1	1	14	100	50	1,305	278,584
21	7	1	1	10	120	45	3,470	288,786
22	24	1	1	18	110	55	2,159	296,789
23	2	1	1	10	100	50	1,247	292,796
24	1	1	1	10	100	45	1,246	294,390
25	25	1	1	18	120	45	2,471	287,996
26	8	1	1	10	120	50	2,548	290,386
27	19	1	1	18	100	45	1,198	271,194

In this work, MINITAB-20 software was used to create linear regression models for the surface roughness and the kerf width. Equations 4 and 5 show the connection between the output and the fixed parameters, respectively.

Regression Equation for the Surface Roughness (4)

Surface Roughness = 1,9739 + 0,1260 Servo Voltage_10 - 0,1947 Servo Voltage_14+ 0,0687 Servo Voltage_18 - 0,7453 Pulse -on_100 - 0,0980 Pulse -on_110+ 0,8433 Pulse -on_120 + 0,0948 Pulse-off_45 - 0,0716 Pulse-off_50 - 0,0232 Pulse-off_55 - 0,157 Servo Voltage*Pulse -on_10 100 - 0,169 Servo Voltage*Pulse -on_10 110 + 0,325 Servo Voltage*Pulse -on_10 120 + 0,209 Servo Voltage*Pulse -on_14 100 - 0,038 Servo Voltage*Pulse -on_14 110 - 0,170 Servo Voltage*Pulse -on_14 120 - 0,052 Servo Voltage*Pulse -on_18 100 + 0,207 Servo Voltage*Pulse -on_18 110 - 0,155 Servo Voltage*Pulse -on_18 120 - 0,009 Servo Voltage*Pulse-off_10 45 - 0,009 Servo Voltage*Pulse-off_10 50 + 0,017 Servo Voltage*Pulse-off_10 55 + 0,184 Servo Voltage*Pulse-off_14 45 - 0,176 Servo Voltage*Pulse-off_14 50 - 0,009 Servo Voltage*Pulse-off_14 55 - 0,176 Servo Voltage*Pulse-off_18 45+ 0,184 Servo Voltage*Pulse-off_18 50 - 0,009 Servo Voltage*Pulse-off_18 55 - 0,101 Pulse -on*Pulse-off_100 45 + 0,080 Pulse -on*Pulse-off_100 50 + 0,022 Pulse -on*Pulse-off_100 55 - 0,338 Pulse -on*Pulse-off_110 45+ 0,331 Pulse -on*Pulse-off_110 50 + 0,007 Pulse -on*Pulse-off_110 55+ 0,439 Pulse -on*Pulse-off_120 45 - 0,411 Pulse -on*Pulse-off_120 50 - 0,028 Pulse -on*Pulse-off_120 55.

Regression Equation for the Kerf Width. (5)

Kerf Width = 297,33 + 3,10 Servo Voltage_10 - 1,41 Servo Voltage_14 - 1,70 Servo Voltage_18 - 9,41 Pulse -on_100 + 3,19 Pulse -on_110 + 6,21 Pulse -on_120 - 9,60 Pulse-off_45 - 3,54 Pulse-off_50 + 13,14 Pulse-off_55 + 14,83 Servo Voltage*Pulse -on_10 100 - 8,70 Servo Voltage*Pulse -on_10 110 - 6,13 Servo Voltage*Pulse -on_10 120 - 13,39 Servo Voltage*Pulse -on_14 100 + 7,54 Servo Voltage*Pulse -on_14 110 + 5,85 Servo Voltage*Pulse -on_14 120 - 1,44 Servo Voltage*Pulse -on_18 100 + 1,16 Servo Voltage*Pulse -on_18 110 + 0,28 Servo Voltage*Pulse -on_18 120 + 3,56 Servo Voltage*Pulse-off_10 45 - 3,03 Servo Voltage*Pulse-off_10 50 - 0,53 Servo Voltage*Pulse-off_10 55 - 4,46 Servo Voltage*Pulse-off_14 45 + 5,54 Servo Voltage*Pulse-off_14 50 - 1,08 Servo Voltage*Pulse-off_14 55 + 0,90 Servo Voltage*Pulse-off_18 45 - 2,51 Servo Voltage*Pulse-off_18 50 + 1,61 Servo Voltage*Pulse-off_18 55 - 7,65 Pulse -on*Pulse-off_100 45 - 5,93 Pulse -on*Pulse-off_100 50 + 13,58 Pulse -on*Pulse-off_100 55 + 12,54 Pulse -on*Pulse-off_110 45 + 4,88 Pulse -on*Pulse-off_110 50 - 17,41 Pulse -on*Pulse-off_110 55 - 4,88 Pulse -on*Pulse-off_120 45 + 1,05 Pulse -on*Pulse-off_120 50 + 3,83 Pulse -on*Pulse-off_120 55.

Table 4. Comparing the Experimental and the Predication Value for SR and KW

Run No.	Exper.SR.	Predic.SR	Absolute Error %	Exper.KW	Predic.KW	Absolute Error %
1	1,806	1,726	4,413	305,583	314,679	2,97661
2	1,222	1,421	16,245	246,404	252,564	2,49996
3	1,101	1,214	10,24	330,375	331,471	0,33174
4	1,567	1,733	10,598	301,584	304,107	0,83658
5	1,49	1,584	6,321	308,783	304,546	1,372161
6	2,494	2,671	7,091	315,182	320,993	1,8437
7	1,871	2,084	11,394	298,389	292,643	1,925674
8	2,471	3,234	30,886	322,381	317,254	1,590354
9	1,484	1,794	20,872	309,583	312,189	0,84178
10	1,695	1,582	6,682	299,989	301,703	0,57135
11	1,384	1,438	3,867	263,985	273,971	3,78279
12	1,201	1,233	2,624	294,379	299,921	1,88261
13	1,787	1,834	2,634	286,381	290,412	1,40757
14	2,409	2,392	0,707	323,981	323,298	0,210815
15	2,729	2,596	4,891	301,589	298,239	1,110783
16	1,632	1,618	0,887	305,578	300,72	1,589774
17	2,579	2,433	5,663	303,184	296,548	2,18877
18	2,748	3,17	15,368	290,385	288,462	0,662224
19	1,379	1,235	10,461	319,176	312,538	2,07973
20	1,305	1,075	17,628	278,584	274,69	1,397783
21	3,47	3,795	9,372	288,786	289,883	0,37987
22	2,159	2,126	1,509	296,789	297,616	0,27865

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23	1,247	1,198	3,968	292,796	294,511	0,58573
24	1,246	1,183	5,077	294,39	291,579	0,954856
25	2,471	3,089	25,018	287,996	288,822	0,28681
26	2,548	1,773	8,83	290,386	294,416	1,38781
27	1,198	1,063	11,29	271,194	267,846	1,234541

From table 4, it can be observed that the error percentage values are identical, which means that the variation between the experimental and the predication values was small, as illustrated in figure 8 and 9.

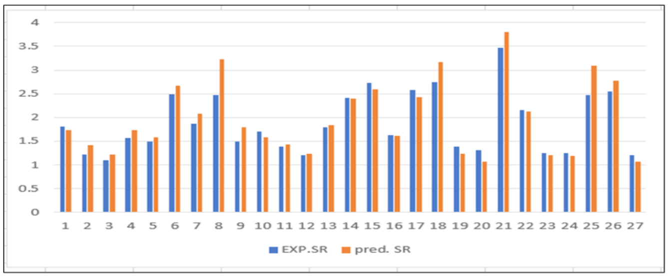

Figure 8. Variance in Experimental and Predication Values of the Process Parameters for the Surface Roughness

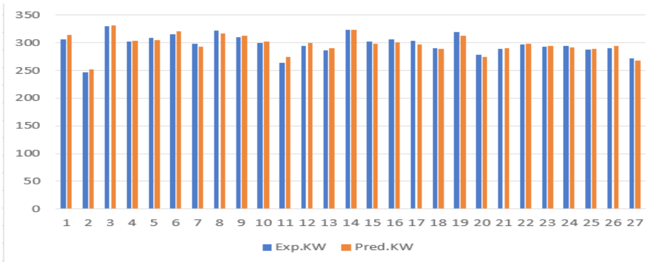

Figure 9. Variance in Experimental and Predication Values of the Process Parameters for the Kerf Width

Figure 8 and 9 illustrate the plots for the corresponding replies. In particular, the plots reveal that both produced models are accurate and suitable for the best response predictions since they follow normalcy and do not display any apparent pattern or unique structure.

Main Effects Plot for Surface Roughness and Kerf Width

Figure 6 shows the major effect of the input factors to investigate their effects on the surface roughness. Specifically, the surface roughness was found to increase when T_{ON} increases, which occurs due to the increase of the spark discharge energy. Additionally, the surface roughness was obtained to be minimal at T_{ON} 100µs, then it grows dramatically at T_{ON} 120µs. It can be observed that when SV grows, SR decreases at first and subsequently increases. The initial drop in SR is caused by a rise in spark intensity, and an increase in servo voltage causes sparking instability, which leads to an increase in SR, which drops slightly with the increase in T_{OFF}. This means that T_{OFF}, as seen in figure 6, has a minimal effect on the SR.

Figure 7 illustrates the influence of SV, T_{ON}, and T_{OFF} on KW. It may be established that KW grows with increasing T_{ON}, which is caused by an increase in the energy of the spark discharge, which is similar to T_{OFF}. However, the SV first increases and then drops, which is due to the instability of the flushing.

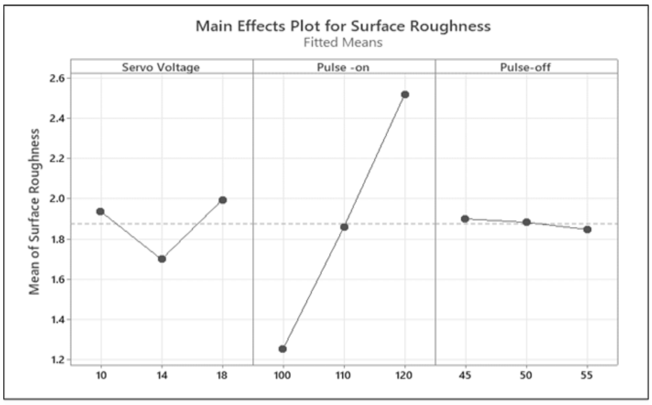

Figure 6. Main Effects Plot for SR

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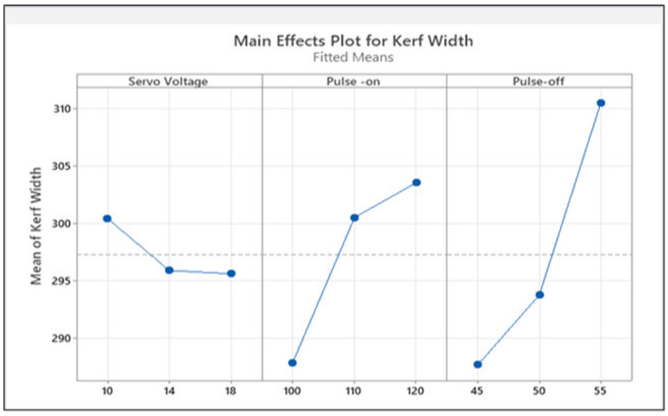

Figure 7. Main Effects Plot for KW

Table 5. General Factorial Regression: Surface Roughness, Kerf Width versus Servo Voltage, Pulse -on, Pulse-off. Analysis of Variance for SR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	18	10,0986	0,56103	11,67	0,001
Linear	6	7,6682	1,27804	26,58	0,000
Servo Voltage	2	0,4423	0,22114	4,60	0,047
Pulse -on	2	7,2130	3,60648	75,00	0,000
Pulse-off	2	0,0130	0,00650	0,14	0,876
2-Way Interactions	12	2,4304	0,20253	4,21	0,025
Servo Voltage*Pulse -on	4	0,5641	0,14102	2,93	0,091
Servo Voltage*Pulse-off	4	0,6714	0,16785	3,49	0,062
Pulse -on*Pulse-off	4	1,1949	0,29873	6,21	0,014
Error	8	0,3847	0,04808		
Total	26	10,4833			

Table 6. General Factorial Regression: Surface Roughness, Kerf Width versus Servo Voltage, Pulse -on, Pulse-off. Analysis of Variance for KW

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	18	8340,5	463,36	6,92	0,004
Linear	6	3863,2	643,87	9,61	0,003
Servo Voltage	2	130,4	65,22	0,97	0,418
Pulse -on	2	1235,5	617,75	9,22	0,008
Pulse-off	2	2497,3	1248,65	18,64	0,001
2-Way Interactions	12	4477,3	373,10	5,57	0,011
Servo Voltage*Pulse -on	4	1821,1	455,27	6,80	0,011
Servo Voltage*Pulse-off	4	250,6	62,66	0,94	0,490
Pulse -on*Pulse-off	4	2405,5	601,39	8,98	0,005
Error	8	535,9	66,99		
Total	26	8876,4			

The analysis of variance summarizes the estimated effects and coefficients for the surface roughness and the kerf width after excluding the negligible effects. According to the analysis of variance (ANOVA), the servo voltage, the T_{ON}, and the T_{OFF} are statistically significant parameters with P-values less than the significance limit of (0,05).

The Grey relational analysis is used to investigate how the process factors impact workpiece quality objectives of "the smaller, the better" characteristic for both surface roughness and kerf width. Step 1 normalizes the data by applying equation 1, and the data becomes as shown in the following table:

Table 7. Grey Relation Analysis

Exp. No.	Grey Relation Generating		Grey Relation Coefficient		GRG	Rank
	SR	KW	SR	KW	Grade	
1	0,702	0,295	0,627	0,415	0,521	17
2	0,949	1	0,907	1	0,954	1
3	1	0	1	0,333	0,667	8
4	0,803	0,343	0,718	0,432	0,575	12
5	0,836	0,257	0,753	0,402	0,578	10
6	0,412	0,181	0,46	0,379	0,419	24
7	0,675	0,381	0,606	0,447	0,526	16
8	0,422	0,095	0,464	0,356	0,41	27
9	0,838	0,248	0,756	0,399	0,577	11
10	0,749	0,362	0,666	0,439	0,553	15
11	0,881	0,791	0,807	0,705	0,756	3
12	0,958	0,429	0,922	0,467	0,694	5
13	0,71	0,524	0,633	0,512	0,573	13
14	0,448	0,076	0,475	0,351	0,413	26
15	0,313	0,343	0,421	0,432	0,427	23
16	0,776	0,295	0,69	0,415	0,553	14
17	0,376	0,324	0,445	0,425	0,435	22
18	0,305	0,476	0,418	0,488	0,453	21
19	0,883	0,133	0,81	0,366	0,588	9
20	0,914	0,617	0,853	0,566	0,71	4
21	0	0,495	0,333	0,498	0,415	25
22	0,553	0,4	0,528	0,455	0,491	18
23	0,938	0,448	0,89	0,475	0,683	6
24	0,939	0,429	0,891	0,467	0,679	7
25	0,422	0,505	0,464	0,502	0,483	19
26	0,389	0,476	0,45	0,488	0,469	20
27	0,959	0,705	0,924	0,629	0,777	

According to the data, the GRA grade for the second trial was 0,954, which was the highest. As a result, this experimental setup, including a servo voltage of 14 V, a pulse on of 100 μs, and a pulse off of 45 μs, is the optimal combination of settings that may concurrently optimize all of the specified response qualities.

CONCLUSIONS

WEDM experiments were carried out with tungsten wire and SS304 as workpieces. The purpose of this study was to find the effects of the WEDM parameters of T_{ON}, T_{OFF}, and SV on the surface roughness and the KW of a hardened steel material utilized in automotive applications. It was found that T_{ON} has the most significant effect on the SR and the KW, followed by the SV and the T_{OFF}. According to the GRA grade for the second trial (0,954), the experimental setup of a servo voltage of 14V, a pulse on of 100μs, and a pulse off of 45 μs was the optimal combination of settings that may concurrently optimize all the specified response qualities. From the comparison of the experimental and the prediction values for the SR and the KW, it was found that the error percentage values are identical.

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